IEEE Guide for Sound Level Abatement and Determination for Liquid-Immersed Power Transformers and Shunt Reactors Rated Over 500 kVA

Sponsor

Transformers Committee
of the
IEEE Power Engineering Society

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Abstract: Guidelines are provided for the selection of suitable sound reduction methods in oil-immersed power transformers and shunt reactors over 500 kVA. Sound-producing sources within transformers and reactors are discussed. Sound abatement procedures are described for achieving various levels of sound reduction in transformer and shunt reactor installations.
Keywords: liquid-immersed power transformers and shunt reactors, sound, sound abatement, sound reduction methods

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

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Introduction

(This introduction is not part of IEEE Std C57.136-2000, IEEE Guide for Sound Level Abatement and Determination for Liquid-Immersed Power Transformers and Shunt Reactors Rated Over 500 kVA.)

This introduction provides some background information to aid in the understanding and usage of this guide.

The proximity of residential areas to some substations and the increasing prevalence of local ordinances specifying property line sound levels have made sound radiation from transformers a factor of increasing significance. Thus, it is of considerable importance that information be available regarding the choice and design of effective methods of sound abatement, which provide a reasonable margin of safety and minimize the probability of community complaints.

In some cases, even recently installed transformers may require the use of sound reduction methods due to residential complaints or changes in the residential zoning codes.

The principal sources of sound radiated by transformers are

a) The core,

b) The windings (and tank), and

c) The cooling equipment.

The core sound, primarily consisting of a double power frequency tone and its harmonics, is generally dominant in overall level. However, on some transformers with forced air cooling, the cooling equipment sound can dominate.

Once the sound levels have been determined at locations of concern, there are various sound level measurements and data manipulation techniques for calculating the desired sound levels to accurately define the problem areas.

Participants

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Ronald W. Stoner
Subhash C. Tuli

Karen Weissman, *Chair, 1997–1999*
Jack W. McGill, *Chair, 1995–1997*

Other individuals who contributed review and comments are:

Dan B. de la Cruz
Andrew P. Dicke
Richard F. Dudley
Donald J. Fallon
A. C. (Sam) Hall

The following members of the balloting committee voted on this standard:

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Raymond Allustiarti
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Contents

IEEE Guide for Sound Level Abatement and Determination for Liquid-Immersed Power Transformers and Shunt Reactors Rated Over 500 kVA

1. Scope

This document is intended to provide guidelines for selecting suitable methods for sound reduction in liquid-immersed power transformers and shunt reactors rated over 500 kVA.

Many sound abatement procedures are described that are presently available for achieving various levels of sound reductions in transformer and shunt reactor installations. For background information, this guide will also discuss the sound-producing sources within transformers and reactors.

2. References

This guide should be used in conjunction with the following publications:

IEEE Std C57.12.00-2000, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.[1]

IEEE Std C57.12.90-1999, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.21-1990 (Reaffirmed 1995), IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA.

NEMA TR1-1993, NEMA Standard Publication on Transformers, Regulators, and Reactors.[2]

[1]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

[2]NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (http://global.ihs.com/).

3. Sources of sound

3.1 General characteristics

Sound coming from the transformer itself, as opposed to cooling fan or pump sound, is tonal in nature, consisting of even harmonics of the power frequency. The predominant source of transformer sound is the core. The low-frequency, tonal nature of this sound makes it harder to mitigate than the broad-band, higher frequency sound that is produced by cooling fans, pumps, and other sources. Not only do low frequencies propagate farther with less attenuation, but also tonal sound is more annoying to the public even in a high sound level ambient. This combination of low attenuation and high perception makes tonal sound the dominant problem in the neighboring community around the transformer. To address this problem, most community sound ordinances impose penalties or stricter requirements for tonal sound. A site may be in compliance with overall sound levels, but out of compliance with tonal levels.

In siting a transformer it is, therefore, critical to consider the dominant tones in the sound spectra, and not just the overall sound levels. These tones will not only dictate the severity of the problem, but also the type of sound mitigation approach that is necessary. For example, if low-frequency tones such as the second and fourth harmonics of the power frequency are present, these are difficult to attenuate with simple sound abatement methods such as a single side wall. In this case an active control system or a full enclosure may be necessary. If very high frequency tones, such as the tenth or twelfth harmonics of the power frequency, are present in the near field, there is a chance that they will attenuate naturally, and no treatment may be necessary if the nearest neighbor is far enough away.

Tones are best measured on a narrow-band spectrum (1-2 Hz bandwidth). Although strong tones are noticeable on one-third or octave band spectra, at higher frequencies two or more tones will always be added together in the same band, making their relative contributions indistinguishable.

3.2 Transformers

The principal sound sources in transformers are:

a) Core sound caused by magnetostriction effects and inter-laminar magnetic forces,
b) Load sound caused by electromagnetic forces in the windings, tank walls, and magnetic shunts due to leakage flux associated with the current, and
c) Cooling equipment sound caused by fans (aerodynamic and motor/bearing sound) and pumps (cavitation and motor/bearing sound).

The frequency spectrum for the core and winding sound is markedly different from that of the cooling equipment. The latter dominates at the lower and higher ends of the frequency spectrum (depending on whether pumps or fans are involved), while the core and winding sound dominates the intermediate frequency range (between 100 Hz and 600 Hz).

3.2.1 Transformer core sound

When a strip of iron is magnetized, it undergoes a very small change in its dimensions (usually only a few parts in a million). This phenomenon is called magnetostriction. This change in dimension is independent of the direction of the flux; therefore it occurs at twice the power frequency. Because the magnetostriction curve is nonlinear, higher-order even harmonics also appear in the resulting vibration of the core at higher induction flux densities.

In addition to magnetostriction effects, magnetic forces within the core will create vibration and thus sound. These forces occur where the flux transfers from the plane of one lamination to the plane of an adjacent

lamination, or at other air gaps. Laminations that are not flat or that have non-uniform thickness or permeability will cause this effect, as will interleaved joints and bolt holes. These holes distort the flux locally, modifying the flux density and flux direction.

Factors influencing the magnitude and frequency components of the transformer core sound include: flux density, core material, core geometry, and wave form of excitation voltage. As in any other mechanical structure, the transformer mounting structure as well as the mechanical resonances of the core and tank walls can have a significant influence on the magnitude of the transformer vibrations and consequently on the sound generated.

3.2.2 Transformer load sound

Load sound is the sound emitted by a loaded transformer in addition to its no-load sound. It is caused by electromagnetic forces resulting from the leakage fields. These forces are proportional to the square of the load current and thus the load sound is proportional to the fourth power of the current (a doubling of the current increases the load sound level by 12 dB). The sources of this sound are the vibrations of tank walls, magnetic shields, and the windings themselves.

The load sound is predominantly produced by the axial and radial vibration of transformer windings. The frequency of this sound is usually twice the power frequency. The compressive electromagnetic forces produce axial vibrations and thus can be a major source of sound. In some cases, the natural mechanical frequency of winding systems may tend to resonate with electromagnetic forces, thereby severely intensifying the load sound.

If an appropriate mechanical design is used for laminated magnetic flux shields and their anchoring to the tank walls (avoiding resonance at the exciting frequency or its harmonics), the sound due to vibrations of these shields is usually of low intensity as compared to the winding sound. However, it is important to take into account the effects of loading beyond nameplate rating in order to avoid saturation of the magnetic shields during operation, which would cause additional sound.

Through several decades the contribution of the load sound to the total transformer sound has remained moderate. Nonetheless, in transformers designed with low induction levels and improved core designs for complying with low sound level specifications, the load sound can become a significant contributor to the overall sound level of the transformer. However, in the majority of these cases, the overall sound level will be determined by the cooling equipment sound level, which generally exceeds the load sound level (except in the case of natural cooling).

The transformer testing standards IEEE Std C57.12.90-1999 and IEEE Std C57.12.91-1999 specify that the sound level measurements on a transformer should be made under no load conditions. As users demand transformers with lower and lower sound levels, there will be a point at which the load sound will become comparable to the core sound. Therefore, when buying a very low sound level transformer, the users may choose to negotiate load sound test procedures with the manufacturers prior to placing their order.

3.3 Shunt reactors

Shunt reactors are usually a significant sound source. The sound is primarily caused by the magnetic “pull” effects of the leakage flux field. The magnetostriction effects of the core steel are not generally significant.

Leakage flux impinges on structural components of the reactor and produces forces acting on them. These forces create vibration and hence sound. The frequency of this sound is normally twice the power frequency.

For “air-core” iron-shielded reactors, forces act upon the parts of the shield that cover the ends of the reactor coil. These forces will act mainly to bend the laminations on edge and can be quite high. The resulting

vibrations depend on the geometry of these "beams" and their support as well as the general clamping structure.

Similar forces and subsequent vibrations are created in the tank walls and on magnetic shielding mounted on the tank.

For gapped-core designs, forces are also created between the core leg packet gaps as well as at the interfaces with the end yokes.

The appropriate mechanical design of the structural components of a reactor to avoid resonance at the exciting frequency is critical in minimizing shunt reactor sound levels.

3.4 Fans and pumps

Sound produced by the cooling fans is usually broad band in nature. Cooling fans usually contribute more to the total sound for transformers of smaller rating and for low-induction transformers. Factors that affect the total fan sound output include tip speed, blade design, number of fans, and the arrangement of the radiators.

Pump sound is normally not significant if the fans are running, although low-frequency sound may be present.

4. Factors affecting sound levels in field operation

The basic principle for a standardized factory test is that the conditions are controlled. A test in accordance with a standard should, in principle, be possible to repeat in any laboratory with the same results. However, in the field, in practical operation, the conditions may be somewhat different. Furthermore, in some cases, even if the operating conditions are known, they may not be feasible to realize in a factory test at a reasonable cost. Therefore, the transformer sound level experienced in practical operation may deviate slightly from the sound level measured during the factory test, even if the principal conditions are the same. In some cases, as for large converter transformers, the difference can be large.

Stated below are some factors that should be considered when defining the sound requirement for a transformer and/or evaluating the need for additional audible sound abatement in order to reach the desired sound level in operation.

4.1 Load power factor

The sound caused by the power-frequency load current normally has only one tone: twice the power frequency. Because of the complicated phase relationship between the core vibrations and the winding vibrations it is considered sufficiently accurate to add the load and no-load sound powers, i.e., assuming an arbitrary phase angle between the two sound sources. Depending on the phase angle of the load current, the total sound level may be higher or lower than the no-load sound level.

The load current also causes a voltage drop inside the transformer that, depending on the load phase angle, may increase or reduce the core flux for the same voltage on the reference winding.

4.2 Loading beyond nameplate rating

When a transformer has had separate no-load sound level and load sound level measurements carried out in the factory (at rated voltage and rated current respectively), the individual sound powers so obtained can be summed logarithmically to obtain an indication of the combined effect of energization and load current. The

differential increase in sound level is usually insignificant. However, if the transformer is loaded with a higher current than was used for the factory test, a higher sound level can be expected.

4.3 Harmonics

4.3.1 Harmonics in the load current

Harmonic content is superimposed upon the load current and hence has a larger impact on the sound level than might be expected from the amplitude of the harmonic current. As the magnetic force is proportional to the square of the current, there will be a cross product between the power-frequency current and the harmonic current, as well as the square of the load current and the square of the harmonic current. Thus, the highest contribution to the sound level due to the harmonic current occurs when the product of the load current and the harmonic current reaches the maximum. The resulting audible tones are at the frequency of the harmonic current plus or minus the power frequency.

It may be mentioned that for large high-voltage direct current (HVDC) converter transformers operating at high load, the sound due to the harmonics can be the most significant sound source. Also, for other transformers feeding rectifiers or other non-linear loads, the impact from the load harmonics can be significant and should be considered.

4.3.2 Harmonics in the excitation voltage

Low order harmonics in the excitation voltage may increase or decrease the transformer core sound, depending on the phase angle, magnitude, and frequency of these harmonics.

4.4 DC magnetization

DC magnetization of a transformer core will increase the transformer audible sound, even at moderate levels of dc magnetization. The reason is that dc magnetization will add a tone at the power frequency and harmonics at the odd multiples of the power frequency to the sound. In addition, the sound at the normal even-order harmonics of the power frequency will all be increased by the dc magnetization.

With the increased use of power electronic equipment both in power transmission systems and in industry, the number of possible sources for dc magnetization, due to rectification, is increasing. This is in addition to the traditional cause due to distributed ground current in dc power systems, including dc feeders to transportation systems. It also may be mentioned that geomagnetic storms may cause severe dc magnetization in transformers connected to long transmission lines. Other known sources include cathodic protection schemes on gas pipelines feeding combustion turbine power plants.

4.5 Resonances

Mechanical or acoustical resonances in practical operation in the actual field installation may increase the sound as compared to factory test results.

5. Factory-installed sound abatement methods

Table 1 is a listing of factory-installed sound control techniques, their principles of operation, their advantages, disadvantages, and their range of achievable sound reduction. This table has been taken in part from the ESEERCO Report, dated Oct., 1981 [B2].[3]

[3]The numbers in brackets correspond to those of the bibliography in Annex A.

There are ways to affect sound level to some extent after the unit is built, e.g., if the tank is in resonance or if a significant portion of the sound is produced by core-to-tank structural vibrations (refer to 5.2.1). Installation of low-sound fans or installation of external sound panels are examples of practical techniques that could be used with existing units. If the user specifies a sound level that is below the value in the NEMA TR1-1993 sound level table, the manufacturer may have to select one or more of the options given in Table 1. The manufacturer's choice will depend on loss evaluations, size and weight limitations, and standard technology. However, factors such as core-joint technology, lamination flatness, steel silicon content, lamination coatings, and clamping are all intrinsically part of the manufacturer's and steel supplier's technology. Much of this information is proprietary with the individual manufacturers and is protected by patents.

Some of these techniques are standard practice, while others are not. Some are experimental in nature and hold varying degrees of promise. Some often discussed methods are mentioned although they may not be as feasible or practical.

Table 1—Factory-installed transformer sound abatement techniques[a]

Sound control technique	Principle of operation	Advantages	Disadvantages	Range of achievable sound reduction in dB(A)
Reduced induction	Reduced magnetostriction	—Wide range of sound reduction available, cost may be offset by evaluated no-load losses	—Increased size and weight —Cost may be increased by evaluated load losses	1–15
Resilient absorbers	Inefficient transmitter of sound	—Effective	—Materials compatibility	8–15
Core and/or tank resonance	Design features could result in core and/or tank resonance	—Sound reduction if resonant correction is effective	—Extremely difficult to reduce sound overall levels —Slight cost increase	2–10
Double-walled tanks with sound panels	Contains sound radiation from tank sides and top	—Effective	—Transformer maintenance difficult, especially oil leaks	6–10
Double-walled tanks no sound panels	Contains sound radiation from tank sides and top	—Moderately effective	—Transformer maintenance difficult, especially oil leaks	5–8
High permeability grain-oriented core steel	Reduced magnetostriction	—Reduction in core losses, cost may be offset by evaluated no-load losses	—Slight increase in costs when comparing highest vs lowest grain-oriented steel	2–7
Filling hollow stiffeners with sand	Reduces vibration of tank wall by providing added mass and damping	—Simple to implement	—Adds weight to transformer —Ineffective on sound emanating from sub-panel vibration between stiffeners	1–3 (Higher if initial tank resonance is high)

Table 1—Factory-installed transformer sound abatement techniques[a] (continued)

Sound control technique	Principle of operation	Advantages	Disadvantages	Range of achievable sound reduction in dB(A)
Core joint technology	Reduced core vibration amplitude	—Reduction in sound and core losses at no additional costs	—May require automatic core processing equipment	1–5
Low-sound fans	Fan blades moving at lower speed produce less sound	—Could be easily retrofitted	—Fan sound usually not objectionable —Requires more fans and controls	2–3
Core vibration isolators	Interrupt path of sound through solid structural members		—Limited sound reduction if used with liquid-immersed transformers	1–3
Flat core laminations	Reduced mechanical stress, (reducing magnetostriction) Reduced inter-laminar forces	—Reduction in sound and core losses at no additional costs		1–2
Low sound tank stiffeners	Reduction in tank vibration	—Sound reduction with very little added costs	—Slight increase in weight and costs —Very limited sound reduction	0–2
Core lamination cementing	Reduced core vibration amplitude		—Very limited sound reduction	0–1
Core clamping	Reduced core vibration amplitude		—Very limited sound reduction Sometimes a sound increase	0–1
Thicker tank wall	Reduced lower frequency transmission		—Relatively expensive, no overall sound reduction	0
Sound panels	Attenuates sound radiation from tank sides	—Effective, simple	—Cost increase	6–10

[a]This table has been taken in part from the ESEERCO Report, dated Oct. 1981 [B2].
It should be noted that sound reductions of less than 3 dB fall within the accuracy and repeatability of measurement and may thus be too small to warrant practical application.

5.1 Typical design methods for sound abatement

Several methods exist that could be termed common sound abatement techniques. These methods and practices should be part of good transformer design and manufacture. If not observed, a higher sound level transformer will result. These methods and practices include the following:

a) Lowering the induction level at rated voltage and frequency
b) Utilizing lower sound core technology
c) Avoiding resonant frequencies in the core and tank by design
d) Assuring the use of flat laminations in the assembly of the core
e) Selecting the proper grain-oriented core steel grade

5.2 Other factory-installed sound abatement methods

There are several other methods of controlling the transformer sound level by factory-installed means.

5.2.1 Vibration isolation of the core from the tank

In oil-cooled transformers, the sound radiated by the transformer tank is caused by both the oil coupling to the tank and the structure-borne excitation of the tank by the rigidly attached core. Accordingly, the vibration isolation mounting of the core could yield a sound reduction of the order of 3 dB. This modest return usually does not justify the complications that are connected with the design and use of a core restraining mechanism needed for shipping. Consequently, most transformer manufacturers mount the core rigidly to the tank bottom.

However, if one utilizes a resilient tank lining as described in 5.2.2 or gas insulation as described in Annex A, then vibration isolation of the core from the tank becomes essential. Without effective vibration isolation of the core, the structure-borne path would control the sound radiation. In this case, the sound reduction would be limited to about 3 dB, unless additional treatments are applied to control the structure-borne vibration after it reaches the tank (e.g., see Clause 6).

To be effective, the vibration isolation mount must be "soft" compared to the tank bottom and at the same time support the weight of the core-and-coil assembly, requirements that are often hard to fulfill simultaneously.

5.2.2 Resilient internal tank lining

A resilient lining applied to the interior surfaces of the transformer tank could be used to reduce the transmission of core sound to the tank walls. As long as the resilient layer is "soft," i.e., has a low impedance, compared with the tank wall so that the "onrushing" oil (driven by the magnetostriction of the core) compresses the resilient layer rather than moving the tank wall, reductions in the radiated sound can be achieved.

This potential insertion loss could only be realized if (a) all interior tank surfaces were covered with the resilient layer, which is not practical on large power transformers having tank walls shielded, and (b) the core was sufficiently isolated from the tank so that structure-borne excitation would be negligible.

5.2.3 Resonant plates attached to the tank wall

Years ago, it was suggested to have an arrangement of thin, rectangular plates oriented parallel to the plane of the transformer tank and supported from the tank on rigid rods. If the thin plates were designed to have their first bending resonant frequency just a few hertz below the transformer tone to be attenuated, they would move approximately 180º out of phase with the transformer tank and, supposedly, would reduce the sound radiated.

Because the vibrating thin plate represents a dipole with its axis perpendicular to the transformer tank wall, and the vibrating transformer wall represents either a monopole or a collection of dipoles with axes in the plane of the wall, it is not clear how a successful compensation could be achieved. However, even if this could be done, the simultaneous maintenance of the proper tuning and, even more importantly, the proper

resonant amplification could not be practically maintained during service. This system has seldom been used.

5.2.4 Double-walled tanks

Surrounding the normal oil-filled tank with a second one separated from the primary tank by air is an effective sound control method, but it is not too practical. The method works for essentially the same reason, as do close-fitting enclosures—the sound radiated from the primary tank is contained. Sound reductions of 5–8d B(A) are obtainable. If sound panels are attached to the outer tank walls, sound reductions of 6–10 dB(A) are possible. While a number of double-wall tank transformers have been built, their disadvantages make their use today uncommon. Most of the disadvantages occur because the secondary tank is an integral part of the transformer. The secondary tank substantially increases the transformer weight and size. This creates shipping and handling problems. Maintenance of double-wall units is more difficult because access to the primary tank is very limited. Oil leaks, in particular, are difficult to detect and fix. In general, double-walled tanks are effective but expensive with serious practical disadvantages.

5.2.5 Thicker tank wall

The increasing of the tank wall thickness has very little or no effect on the overall sound level reduction and the material costs do not justify the results.

5.2.6 Exterior sound panels

Sound panels attached to the outer tank walls, typically in between tank reinforcing ribs, can be practical, and sound reductions on the order of 6–10 dB(A) might be possible. Many such transformers have been manufactured and are common. The panels can be readily removed (in the event that an oil leak occurs behind a panel). There is only a small increase in weight and no increase in size, as the panels are installed in between the tank reinforcing ribs.

6. Field-installed sound abatement methods

Table 2 is a listing of field-installed sound control techniques, their principles of operation, their advantages, disadvantages, and their range of achievable sound reduction. This table has been taken in part from the ESEERCO Report [B2].

Transformer sound control measures applied outside the transformer and the materials necessary to implement them have been examined to determine which ones are feasible and practical and have sufficient life expectancy to warrant development of prediction methods for their expected acoustic performance. Feasibility is considered to be the capability for being used or dealt with successfully. Practicality refers to established or proven usefulness (as opposed to theoretical, speculative, or ideal considerations), which inherently includes cost as a factor. Life expectancy is considered to be the length of time a transformer can remain in service, maintaining its function, without undue risk, at acceptable (normal) levels of maintenance. All three of these factors are qualitative in nature and, therefore, subject to different interpretations.

One measure of the practicality of these sound control methods is shown in Table 2, which has been compiled from existing transformer installations. This table testifies to the practicality (proven usefulness) of barriers, walk-in and barrier enclosures, close-fitting enclosures, and tank-supported panels.

Some of the techniques shown in Table 2 are in common usage, while others are not. There are cases referenced in the ESEERCO Report in the literature [B2] for which attached masses, tuned vibration dampers,

resonators, and/or resonant plates have been attached to the tank wall. In most of these cases, these items were used to “fix” a bad tank design.

Table 2—Field-installed sound abatement techniques[a]

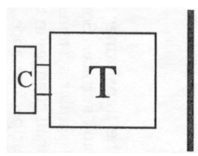
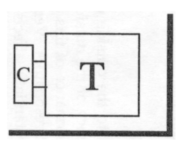
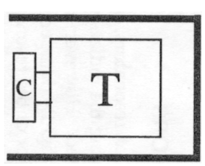
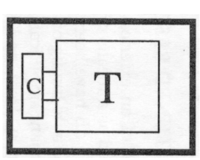
Sound abatement technique	Sketch	Principle of operation	Advantages	Disadvantages	Range of achievable sound reduction dB(A)
Single barrier		Blocks direct path between source and receiver	—Standard construction —Well suited for retrofit —Can serve as fire barrier —Standard transformer construction is retained	—Possible bus work interference —Effective in one direction only —Low frequency diffraction near top and sides, causing sound leakage	7–10
Two-sided barrier		Blocks direct path between source and receiver	—Standard construction —Well suited for retrofit —Can serve as fire barrier —Standard transformer construction is retained	—Effective for two directions only —Possible bus work interference —Increase in sound in uncovered areas; low frequency diffraction causing sound leakage.	7–10
Three-sided barrier		Blocks direct path between source and receiver	—Standard construction —Well suited for retrofit —Can serve as fire barrier —Standard transformer construction is retained	—Increase of sound in unblocked directions; low frequency diffraction causing sound leakage —May lose cooling efficiency —Possible bus work interference	7–10 NOTE—Lining the interior surfaces of the barrier wall in the shadow zones can increase performance and prevent build-up in the unblocked directions.
Four-sided barrier		Blocks direct path between source and receiver	—Standard construction —Well suited for retrofit —Can serve as fire barrier —Standard transformer construction is retained	—Limited effectiveness if not lined —Possible bus work interference —Loss of cooling efficiency —Maintenance and removal difficult —Low-frequency sound leakage	Unlined 5–9 Lined 7–12

Table 2—Field-installed sound abatement techniques[a] (continued)

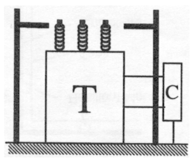
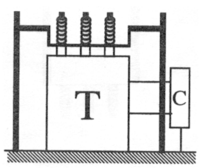
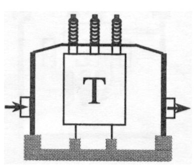
Sound abatement technique	Sketch	Principle of operation	Advantages	Disadvantages	Range of achievable sound reduction dB(A)
Four-sided barrier enclosure Tank cover not covered		Contains sound radiated from tank sides and blocks direct path between tank cover and receiver	—Standard construction —Well suited for retrofit —Can serve as fire barrier —Standard transformer construction is retained —More effective than four-sided barrier (previous) —Moderate cost	—Possible bus work interference —Heat exchangers must be rearranged —Fan sound is not contained —Radiator connections may need vibration isolation	13–18 NOTES —Performance can be increased considerably by lining the interior surfaces of the barrier wall above the tank cover level. —May need flexible connections in heat exchange pipes.
Four-sided barrier enclosure; Extended turrets and integral tank cover enclosure		Contains sound radiated from tank sides and tank cover	—Very cost effective as an original option: i.e., transformer with extended turrets and integral tank cover —Little deviation from standard transformer design —No transportation problem	—As a retrofit, not as cost effective as an original option —Heat exchangers must be rearranged —Radiators may need vibration isolation —Fan sound is not contained	16–25 NOTES —For high performance flexible connectors in cooling equipment pipes are needed. —Vibration isolation of the transformer is required.
Walk-in enclosure; Prefabricated lined sheet metal		Contains sound radiated from tank and cooling equipment Ducted silenced cooling air intake and exhaust Transformer is vibration-isolated from its foundation	—Highly effective —Fast assembly and disassembly —Can be designed to fit many sizes —Fan sound is also attenuated —Good appearance	—Expensive —Effective use requires highly standardized transformer designs —Maintenance	16–25 NOTES —Enclosure has effective interior sound absorbing treatment. —Mufflers and flexible connections in cooling-air intake and exhaust ducts are required. —Enclosure ventilation openings are acoustically treated.

Table 2—Field-installed sound abatement techniques[a] (continued)

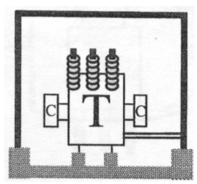
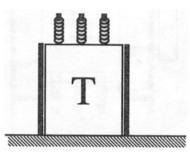
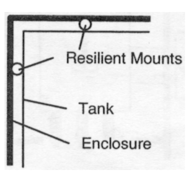
Sound abatement technique	Sketch	Principle of operation	Advantages	Disadvantages	Range of achievable sound reduction dB(A)
Walk-in enclosure; Building–like		Building of heavy construction completely surrounds transformer Connections to transformer via cables	—Very high sound reduction —Personnel access —Appearance can be adjusted to resemble neighboring buildings —Attractive option in connection with urban switching stations	—Expensive —Requires underground cable connections or modifications of bushings —Not attractive for retrofit	25–40 NOTES —Performance is usually controlled by openings and gaps. —Vibration isolation mounting of the transformer is required. —Highest performance may require interior sound-absorbing treatment.
Close-fitting enclosure; Free standing		Closely surrounds the vibrating tank surface and contains the radiated sound	—Attractive for retrofit —No major modifications of the transformer are required, especially if the tank cover is not covered —May improve visual appearance	—Labor-intensive field fitting —Maintenance —Reduces accessibility of transformer —May reduce self-cooled capability and highest power rating —Not transportable as a unit	10–15 NOTE—Performance strongly depends on airspace depth, mass per unit area of the enclosure panels, and sound absorption in the airspace. Fan sound remains unaffected.
Close-fitting enclosure; Resiliently tank-mounted		Same as free standing (previous), but the enclosure may be excited to vibration via the resilient mounts.	—Same as free standing (previous) —Can be transported with the transformer as a unit	—Same as free standing (previous), except transportability —Difficulties with even loading of the resilient mounts —Acoustical performance not as good as free standing	8–13 NOTE—Performance strongly depends on effectiveness of the resilient mounts, airspace depth, mass per unit area of the enclosure panels and sound absorption in the airspace.

Table 2—Field-installed sound abatement techniques[a] (continued)

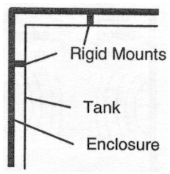
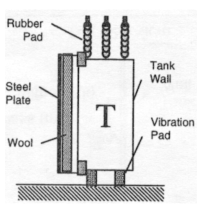
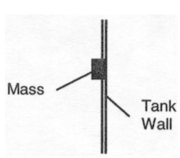
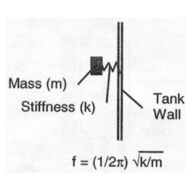
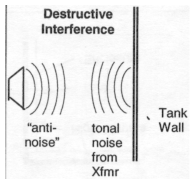
Sound abatement technique	Sketch	Principle of operation	Advantages	Disadvantages	Range of achievable sound reduction dB(A)
Close-fitting enclosure; Rigidly tank-mounted		Same as resiliently tank-mounted (previous), but structure flanking is stronger.	—Same as resiliently tank-mounted (previous) —Easier and less expensive construction than free-standing or resiliently tank-mounted —No problem with uneven loading of isolators and heat expansion	—Same as resiliently tank-mounted (previous), except no resilient mounts —Acoustical performance not as good as free standing or resiliently tank-mounted.	5–9 NOTE—Performance strongly depends on viscous damping of the enclosure panels, panel thickness, and the number of rigid connections.
Tank-supported wall panels		Essentially the same as resiliently and rigidly tank-mounted (previous). Usually offered as an option by the transformer manufacturer and covers only the sides of the tank.	—Same as free standing and resiliently tank-mounted —Attractive original purchase option either alone or in combination with low flux density —If transformer is ordered to accommodate panels, retrofit application is fast and easy.	—Fan sound is unaffected —Tank cover radiation controls maximum achievable sound reduction —May reduce self-cooled rating of transformer	4–10 NOTE—Performance depends on the same parameters as listed in resiliently tank-mounted and rigidly tank-mounted (previous).
Attached masses		Added mass detunes the tank wall resonance frequency from tonal core excitation frequency and also increases effective mass of wall.	Easy, effective retrofit to fix bad tank design	Little, if any, reduction of non-resonant response.	1–4 NOTE—Applies only at a single frequency only if excitation frequency coincided with a resonant frequency of the untreated tank wall panel; Seldom used.
Tuned vibration damper		Increases the effective impedance of the wall at the attachment point at $f = f_0 \pm f$. It also detunes the panel resonance.		—Tuning is sensitive to temperature —Works only at a single frequency.	1–4 Applies only at tuned frequency; Seldom used

Table 2—Field-installed sound abatement techniques[a] (continued)

Sound abatement technique	Sketch	Principle of operation	Advantages	Disadvantages	Range of achievable sound reduction dB(A)
Active sound cancellation		Acoustic and vibration actuators, placed on or near the tank wall, produce an “anti-sound” signal that cancels tonal sound from the transformer before it radiates. Actuators are driven by DSP controllers that use error sensing microphones as input.	—Well suited for retrofits —Global or directional quieting —Full access to transformer —Does not cause heat build-up —Maintains standard transformer design —Very effective at low frequencies —Adapts to transformer sound changes	—Cost can be high —Impractical for sound problems with tones above 500 Hz —Requires some maintenance —Must be professionally designed and installed	Reduction: 5–25 at 120 Hz 4–15 at 240 Hz 3–12 at 360 Hz 3–12 at 480 Hz NOTE—Fan sound remains unaffected.

[a]This table taken in part from the ESEERCO Report, dated Oct., 1981 [B2].

6.1 Typical field-installed sound abatement methods

Several methods of field-installed sound abatement are in common use. These methods and practices (detailed in Table 2) include the following:

a) Barriers,
b) Enclosures, and
c) Tank-supported wall panels.

Since transformers are typically considered to have a lifetime of 25 to 40 years, it is desirable for any sound control measures to have the same expected lifetime. Barriers, enclosures, and tank-attached panels can be fabricated from several materials. In addition, there are several choices for absorption materials, vibration isolation, etc. A listing of such materials, with known advantages, disadvantages, and estimated lifetimes, can be found in the ESEERCO Report [B2].

6.1.1 Absorption materials

When four-sided barriers, barrier enclosures, and walk-in enclosures are used, sound absorption material (typically placed on the inner side of the walls) is required to prevent the reverberant build-up of sound levels within the enclosed space around the transformer. Three materials that have been widely used for transformer sound control are fiberglass, mineral wool, and resonator blocks. The fiberglass and mineral wool have been used predominantly in either standard acoustical panels or built-up metal panel walls where their modest cost, relative ease of handling, and broadband sound absorption are very desirable. The resonator masonry blocks have been widely used in masonry barriers and enclosures where the sound absorption is accomplished at a small, incremental price over that of standard structural block.

6.1.2 Vibration isolation materials

For either the barrier enclosures or walk-in enclosures, it is important to evaluate the use of vibration isolation materials to prevent vibration transmission from the transformer to the enclosure wall. If not used, energy transmitted to the wall can be radiated as sound and, consequently, reduce the effectiveness of the enclosure. Vibration isolation can be achieved either by placing isolation material under the transformer or under the enclosure and ensuring that no parts of the transformer or its appendages are in contact with the enclosure. The most commonly used method, at least for new installations, is to place the isolation under the transformer. For a retrofit application using a metal panel barrier enclosure, the most practical method is to place the isolation under the enclosure wall. Wide-spread experience indicates that steel springs and neoprene mounts or pads are the materials that are most commonly used. Where maximum isolation is required, a combination of springs and neoprene pads is used in series. This capitalizes on the superior low-frequency isolation of the springs and the superior higher-frequency isolation of the neoprene.

6.1.3 Barrier spacing

When installing or designing barriers or enclosures near tank walls, care should be taken to avoid spacing between the tank wall and the barrier at even multiples of the power frequency half wave length (approximately 1.5 m, 3 m, 4.5 m, etc.). These spacings will result in standing waves that may amplify sound levels at some locations between the transformer and the barrier, but are not expected to have an effect outside the barrier.

6.2 Other field-installed sound abatement methods

6.2.1 Attached masses

Added tank wall mass is a useful method for reducing the resonant response of a tank that is poorly designed. For a well-designed tank, added mass produces no discernible sound level reductions. Therefore, while the measure is well understood, it is not practical as a general method because the majority of transformers are designed with tanks exhibiting minimal resonant responses.

6.2.2 Tuned vibration dampers

Experience with tuned vibration dampers has shown that while one area of a tank can be damped, another area will generally vibrate at a higher amplitude. Because multiple tones are generally involved, it has proved to be very difficult to achieve any overall sound reduction via this measure. Tuned thin plates attached to the tank are one form the dampers could take. Such a design is susceptible to physical damage and could be detuned by accumulations of ice or snow in cold climates. Additionally, the tuning is temperature-sensitive. Hence, the use of tuned vibration dampers has to be considered not feasible or practical as a general method of transformer sound reduction.

6.2.3 Tuned resonators

The use of an exterior array of resonators, attached to the outside of the transformer tank, has been proposed as a means of reducing the radiation efficiency of the outside tank surface. Sound reductions up to 14 dB have been reported. However, the performance of this and similar systems depends on a very accurate tuning of a very lightly damped array of resonators. Very small changes in the tuning or in the resonant amplification factor of the resonators substantially affects their performance. Consequently, snow, rain, frost, and even temperature changes due to the transformer loading could cause severe detuning and cause the resonators to be ineffective. For this reason and because the resonator elements are susceptible to physical damage, this technique is not feasible.

7. Active sound cancellation

Active sound cancellation may take four distinctly different forms, as follows:

a) Sound cancellation on or near the tank
b) Sound cancellation outside the tank, in the acoustic far field
c) Sound cancellation inside the tank
d) Harmonic suppression by flux cancellation

The first method, cancellation on or near the tank, is the most commercially developed to date, and is discussed in detail in 7.1. The latter three methods have been tried with varying degrees of success, but have not been used in long term practical applications. These methods are summarized in 7.2.

Active sound cancellation is most effective at lower frequencies, namely two, four, and six times the power frequency (see Table 2 for typical reductions). In some cases, a resonance may occur at higher frequencies, which cannot be readily controlled using active sound control.

7.1 Sound cancellation on or near the tank

In principal, acoustic near-field cancellation is achieved by placing an array of baffled loudspeakers as near to the transformer tank as is practically feasible, and driving them 180° out-of-phase with the motion of the nearest portion of the tank alone.

Another realization of the same principle is by use of displacement actuators, placed directly on the tank wall, which alter the deflection shape of the tank wall at specific frequencies so that the wall is no longer an efficient sound radiator.

These systems are newly commercialized and must be customized for each application. The performance of these systems, as with tuned resonators mentioned in 6.2.3, will also depend on various factors such as local terrain, weather conditions, and to an extent, the ambient temperature fluctuations. Sophisticated computer hardware and software are also required to monitor and control these systems. However, active sound control is emerging as a practical, effective solution to transformer sound.

7.2 Other active sound cancellation techniques

7.2.1 Sound cancellation outside the tank in the acoustic far-field

For far-field cancellation, an array of acoustic actuators (e.g., loudspeakers) is located typically 1.3–2 m away from the transformer.

By moving away from the transformer tank, a larger surface area must be covered by the array of acoustic actuators. In addition, the need to control wind-induced phase shifts between original sound and anti-sound may arise. These factors make far-field cancellation more technically challenging and more expensive.

It is difficult in practice to create a uniform “quiet zone” by canceling in the far-field. In fact, the sound levels may even increase in certain locations due to the presence of the anti-sound source. Because of these drawbacks, limited work has been done to date to implement this method.

7.2.2 Sound cancellation inside the tank

It seems logical to attempt to cancel the sound as near to the source as possible. An early British patent (patent #897-859) suggests inserting a “suitable transducer” in the oil between the core and tank wall, and

operating it with a current that produces displacements of the oil equal in amplitude but opposite in phase to that produced by the transformer core in order to reduce the radiated sound.

The idea of achieving cancellation with a single or with very few transducers is based on the assumption that the tank wall vibrations are caused solely by the compression of the oil volume in the tank. However, transformer oil is basically an incompressible fluid. The tank walls are excited by the inertial motion of the oil as it tries to “slosh” back-and-forth between the opposite faces of the transformer yoke and legs, rather than by any net periodic volume change. Thus, cancellation of the tank wall excitation with a few interior transducers does not seem feasible.

Techniques involving placing structural displacement actuators directly on the internal vibrating structure of the transformer are currently being investigated. These techniques hold promise, but are not yet commercialized.

7.2.3 Harmonic suppression by flux cancellation

Successful attempts were made to reduce the amplitude of the transformer sound by injecting a relatively small voltage at twice the power frequency of the supply. The injected voltage was derived from a motor-alternator set and its phase and amplitude adjusted until the intensity of the fourth harmonic tone became a minimum. A steady reduction of 15 dB–20 dB has been achieved for the fourth harmonic tone and for all the other higher order harmonics. The amplitude of the second harmonic tone remained unaltered by this flux cancellation. While the results are significant, the technique has not been examined in enough detail to determine if it could be implemented in a practical, cost-effective manner.

It may be mentioned that power quality considerations could limit the amplitude of harmonic voltage that can be injected into a power system.

8. Useful sound level information

The test procedure for determining the sound level of a transformer or reactor is fully described in Clause 13 of IEEE Std C57.12.90-1999.

There are two values that are commonly used to express the amount of sound emitted by a source; these values are the sound pressure level and the sound power level.

8.1 Sound pressure level

The sound pressure level is a measure of the pressure fluctuations in the air that are caused by a source. It is these pressure fluctuations that our ear hears and which are measured by the microphone of a sound pressure level meter. The sound pressure level will vary with the distance from a source and with the environment in which the sound is located. The closer to a sound source, the higher the sound pressure level.

The sound pressure level, L_p in decibels (dB), is twenty times the logarithm to the base ten of the ratio of a given sound pressure (p) to a reference pressure (p_o) of 20 micropascals (μPa), or

$$L_p = 20 \times \log_{10}\left(\frac{p}{p_o}\right) \tag{1}$$

The reference pressure is the rms value of a sine wave.

8.2 Sound power level

The sound power level is the amount of sound energy radiated by a particular source. The larger the sound power radiated by a sound source, the higher the sound pressure level at a given position relative to the source.

The sound power level, L_w, in decibels (dB), is equal to ten times the logarithm to the base ten of the ratio of a given sound power (w) to the reference power (w_o) of 10^{-12} watt, or

$$L_w = 10 \times \log_{10}\left(\frac{w}{w_o}\right) \tag{2}$$

The sound power level of a sound source cannot be measured directly. The sound power level is calculated by measuring the sound pressure level at a known distance from the sound source, averaging the measured sound pressure level (see 8.4.1) and then summing this average sound level over the measurement surface. This calculation can be performed using Equation (4) in 8.4.2.

8.3 A-weighting sound scale

The sound pressure level can be measured using octave band, one-third octave band, discrete frequency, or A-weighted filters.

The A-weighting scale is commonly used to measure equipment and community sound levels as it simulates the frequency response of the human ear to sounds of different frequencies. The human ear is very responsive to middle-frequency and high-frequency sounds, but is much less responsive to low-frequency sounds. To simulate the human ear, the A-weighting scale adjusts the sound level of low frequencies downward while providing relatively little adjustment to the high- and midrange-frequencies.

A-weighted frequency corrections are given in Table 9 and Table 10 of IEEE C57.12.90-1999 for one-third octave band and discrete frequency sound levels respectively.

8.4 Sound level calculations

8.4.1 Average sound pressure level (L_p)

The average transformer sound pressure level, L_p, shall be computed by averaging the ambient-corrected sound pressure levels measured at each microphone location and for each frequency band (either A-weighted, one-third octave band, or discrete frequency) using the following equation:

$$L_p = 10 \times \log_{10}\left[\frac{1}{N}\sum_{i=1}^{N} 10^{(L_i/10)}\right] \tag{3}$$

where

L_p is the average sound pressure level in dB,
L_i is the sound pressure level measured at the i^{th} location for the A-weighted sound level, for a one-third octave frequency band, or for a discrete frequency,
N is the total number of sound measurements.

The arithmetic mean of the measured sound pressure levels may be used to determine the average transformer sound pressure level when the variation of the measured levels is 3 dB or less, or when an approximate value of the average transformer sound level is desired.

8.4.2 Sound power level calculation (L_w)

The sound power level (L_w) shall be computed for each frequency band (either A-weighted, octave band, one-third octave band, or discrete frequency) using the following equation:

$$L_w = L_p + 10 \times \log_{10}(S) \tag{4}$$

The measurement surface area (S) is the vertical area (in square meters) enveloping the transformer (measurement surface) on which the sound measurement points are located, plus the horizontal area bound by the vertical measurement surface. Alternatively, for large transformers, the measurement surface area is approximately equal to 125 percent of the vertical area enveloping the transformer (measurement surface).

8.4.3 Computation of A-weighted sound power level

The transformer A-weighted sound power level can be computed using the following procedures when the A-weighted sound level has not been measured.

8.4.3.1 Octave or one-third octave band measurements

When a transformer sound power level has been computed on an octave band or one-third octave band basis, the A-weighted sound power level can be computed using the following equation:

$$L_w(\mathrm{A}) = 10 \times \log_{10}\left[\sum_{j=1}^{19} 10^{[L_w(f_j) + K_j]/10}\right] \tag{5}$$

where

$L_w(\mathrm{A})$ is the estimated A-weighted sound power level, dB re: 10^{-12} watt,
$L_w(f_j)$ is the sound power level in the f_j third octave frequency band [computed, e.g., from Equation (4)],
K_j is the A-weighted correction for the jth frequency band,
f_j are the one-third octave band frequencies for measuring transformer sound.

where $j = 1$ refers to the one-third octave band with a 62.5 Hz center frequency and, subsequently, $j = 19$ refers to the one-third octave band with a 4000 Hz center frequency. If full-octave band data is used, $j = 1$ refers to the 62.5 Hz center-frequency octave band through $j = 7$, where $j = 7$ refers to the 4000 Hz center-frequency octave band.

8.4.3.2 Narrow-band frequency measurements at discrete frequencies

When a transformer sound power level has been computed using narrow-band measurements at discrete frequencies, the core/tank A-weighted sound power level shall be computed using the following equation:

$$L_w(\mathrm{A}) = 10 \times \log_{10}\left[\sum_{k=1}^{7} 10^{[L_w(f_k) + K_k]/10}\right] \tag{6}$$

where

- L_w (A) is the estimated A-weighted sound power level, dB re: 10^{-12} watt,
- f_k are the seven discrete frequencies for measuring transformer sound (Table 10 of IEEE C57.12.90-1999),
- $L_w(f_k)$ is the sound power level in the k^{th} frequency, dB re: 10^{-12} watt,
- K_k is the discrete frequency correction for the k^{th} frequency (Table 10 of IEEE C57.12.90-1999).

where $k = 1$ refers to the discrete measurement at 60 Hz and, subsequently, $k = 7$ refers to the discrete measurement at 720 Hz.

The use of 10 discrete frequencies may be desirable for a more detailed analysis, particularly in the presence of dc effects, and the A-weighted sound power level could be computed using the following equation:

$$L_W(\mathrm{A}) = 10 \times \log_{10}\left[\sum_{k=1}^{10} 10^{[L_w(f_k) + K_k]/10}\right] \tag{7}$$

where

- L_w (A) is the estimated A-weighted sound power level, dB re: 10^{-12} watt,
- f_k are the ten discrete frequencies for measuring transformer sound (see below),
- $L_w(f_k)$ is the sound power level in the k^{th} frequency, dB re: 10^{-12} watt,
- K_k is the A-weighted correction for the k^{th} frequency (obtain by interpolation from Table 9 and Table 10 of IEEE C57.12.90-1999).

where $k = 1$ refers to the discrete measurement at 120 Hz and, subsequently, $k = 10$ refers to the discrete measurement at 1200 Hz.

Discrete frequency measurements should only be used for estimating transformer core/tank sound ratings because the sound is not measured over the entire audible frequency spectra. This measurement technique is therefore not applicable when cooling fans or pumps are operating.

If a full narrow-band spectrum were measured, the sum would be over all frequencies in the spectra as opposed to the seven or ten discrete frequencies listed above.

Annex A

(informative)

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Annex B

(informative)

Estimation of far-field transformer sound levels

These equations are provided as a basic method to estimate transformer sound pressure levels at a specific receiver location in the far field. For simple installations, these equations will provide an accurate estimation of transformer sound emissions at distances greater than twice the largest dimension of the transformer. Sound propagation is affected by various factors such as atmospheric absorption over distances greater than 100 m, complex terrain, interceding barriers, and reflective surfaces. An explanation of these factors is beyond the scope of this text, however, they are mentioned to make the user aware of their potential influence. If site conditions exist which will influence the sound propagation, the user of this guide should reference acoustic propagation texts or consult an individual experienced in conducting sound propagation calculations. In the following text and examples, the term IEEE locations refer to the standard measurement positions as per standard IEEE C57.12.90-1999, Figure 29.

Step 1. Determine transformer sound power level (L_w)

$$L_w = L_{p_{\mathrm{IEEE}}} + 10 \log_{10} (\text{surface area}) \tag{B1}$$

where

L_w is transformer sound power level [dB(A)],
$L_{p_{\mathrm{IEEE}}}$ is transformer sound pressure level at IEEE locations [dB(A)],
surface area is IEEE measurement surface area in m^2,
= 1.25 transformer height x measurement perimeter. (B2)

Step 2. Calculate sound pressure level at a specific location

Assuming hemispherical sound wave radiation

$$L_{p_R} = L_w - 10 \log_{10}(2\pi R^2) \tag{B3}$$

where

L_{p_R} is sound pressure level at the specified distance, R [dB(A)],
L_w is transformer sound power level [dB(A)],
R is distance from transformer to location in m.

This resulting L_p calculated from Step 2. will provide an estimate for a single transformer installation. If there are multiple transformers proceed to Step 3.

Step 3. Multiple transformer installations

If there are multiple transformers then repeat Step 1 and Step 2 for each transformer. Combine the resulting sound pressure level for each transformer using the following equation:

$$L_{P_{\mathrm{total}}} = 10 \log_{10}[10^{(Lp1/10)} + 10^{(Lp2/10)} + \ldots 10^{(Lpn/10)}] \tag{B4}$$

where

$L_{p_{\text{total}}}$ is total sound pressure level of all transformers [dB(A)],
L_{pn} is sound pressure level of the n^{th} transformer [dB(A)].

Example 1.

The maximum allowed sound level at a property line is 53 dB(A). The property line is 122 m from the transformer. The height of the transformer is 6.1 m and the perimeter is 18.3 m. What should the maximum allowable sound pressure level of the transformer be at the IEEE locations?

L_{p_R} = 53 dB(A), R = 122 m, h = 6.1 m, p = 18.3 m

Using Equation (B2)

Surface area = 1.25 h × p = 1.25 × (6.1 m) × (18.3 m) = 139.5 m^2

Rewriting Equation (B3) $L_w = L_{p_R} + 10 \log_{10} (2\pi R^2)$

$\Rightarrow \quad L_w = 53 \text{ dB(A)} + 10 \log_{10} [2\pi(122^2)] = 102.7 \text{ dB(A)}$

Using Equation (B1) $L_w = L_{p_{\text{IEEE}}} + 10 \log_{10} (\text{surface area})$

$\Rightarrow \quad L_{p_{\text{IEEE}}} = 102.7 \text{ dB(A)} - 10 \log_{10} (139.5) = 81.3 \text{ dB(A)}$

The maximum allowable sound pressure level of the transformer at the IEEE locations is 81 dB(A).

Example 2.

The measured sound pressure level of a medium power transformer is 62 dB(A). The property line is 30 m away from the transformer. The height of the transformer is 5 m, and the measurement perimeter is 16 m. What is the sound pressure level of the transformer at the property line?

$L_{p_{\text{IEEE}}}$ = 62 dB(A), R = 30 m, h = 5 m, p = 16 m

Using (B2)

Surface area = 1.25 h × p = 1.25 (5 m) × (16 m) = 100 m^2

Using Equation (B1)

$$L_w = L_{p_{\text{IEEE}}} + 10 \log_{10} (\text{surface area}) = 62 \text{ dB(A)} + 10 \log_{10}(100) = 82 \text{ dB(A)}$$

Using Equation (B3)

$$L_{p_R} = L_w - 10 \log_{10}(2\pi R^2) = 82 \text{ dB(A)} - 10 \log_{10} [2\pi(30^2)] = 44.5 \text{ dB(A)}$$

The sound pressure level at the property line is 44.5 dB(A).

Example 3.

A substation consists of two transformers, each with an IEEE measurement surface area of 84 m^2. Each transformer radiates an average sound pressure level of 81 dB(A) at the IEEE measurement surface. The nearest property boundary is 40 m from the first transformer and 50 m from the second transformer. What is the expected sound pressure level at the nearest property boundary?

$$L_{p_{\mathrm{IEEE}}} = 81\ \mathrm{dB(A)},\ R_1 = 40\ \mathrm{m},\ R_2 = 50\ \mathrm{m},\ \text{surface area} = 84\ \mathrm{m}^2$$

Using Equation (B1)

$$L_w = L_{p_{\mathrm{IEEE}}} + 10\ \log_{10}\ (\text{surface area}) = 81\ \mathrm{dB(A)} + 10\ \log_{10}(84) = 100\ \mathrm{dB(A)}$$

Then using Equation (B3)

For Transformer 1:

$$L_{p_1} = L_w - 10\ \log_{10}\ (2\pi R_1^2) = 100\ \mathrm{dB(A)} - 10\ \log_{10}[2\pi(40)^2] = 60\ \mathrm{dB(A)}$$

For Transformer 2:

$$L_{p_2} = L_w - 10\ \log_{10}\ (2\pi R_2^2) = 100\ \mathrm{dB(A)} - 10\ \log_{10}[2\pi(50^2)] = 58\ \mathrm{dB(A)}$$

Finally, using Equation (B4)

$$L_{p_{\mathrm{total}}} = 10\log_{10}[10^{(60\ \mathrm{dBA}/10)} + 10^{(58\ \mathrm{dBA}/10)}] = 62\ \mathrm{dB(A)}$$

The sound pressure level at the nearest property boundary is 62 dB(A).